Active Fiber Composite Material Systems for Structural Control Applications

A Review of the Active Fiber Composite Consortium (AFCC)

Aaron A. Bent
Continuum Control Corporation

Sponsor: AFOSR-DARPA
Program Manager: Dr. Spencer Wu, Dr. Wallace Smith

DARPA Smart Structures Technology Interchange Meeting
Baltimore, MD
June 26-27, 2000

Continuum Control Corporation

Mission

- Develop and manufacture integrated devices & systems for sensing and control using Smart Materials

Current Focus Areas

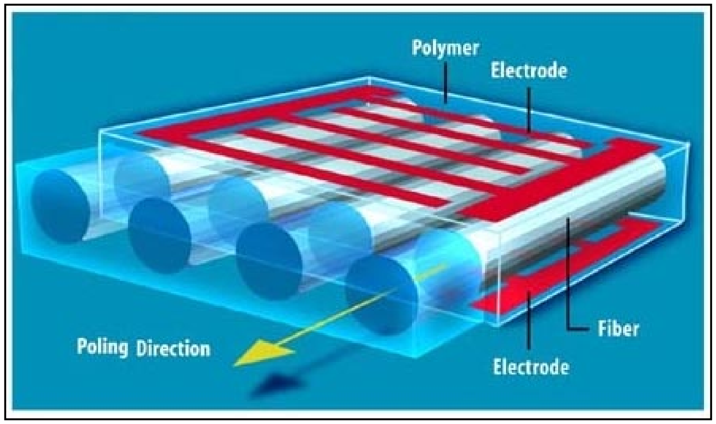
- Active Fiber Composites, Single Crystal AFCs
- High Efficiency Electronics, Self-Powered Damping Systems
- Integrated Devices, Energy Harvesting

Status

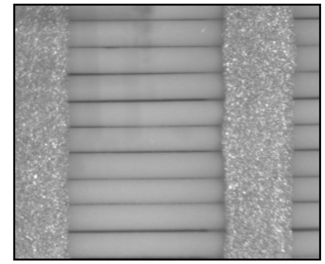
- Founded July 1998
- Both government R&D and commercial programs

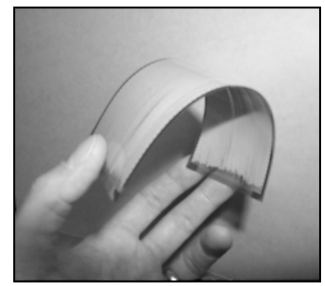
Active Fiber Composite Technology

- Active Fiber Composites (AFCs) originated from work started by Bent & Hagood (1992), sponsored by ONR (Dr. Wallace Smith)



- High Performance
- Directional Actuation
- Conformable
- Robust
- Large Area





Piezoelectric Fibers: → *Stiffness and actuation authority*

Polymer Matrix: → *Load transfer mechanism*

Interdigital Electrode: → *Align field with fibers*

Glass Fibers: → *Integral reinforcement*

Foundation Active Fiber Composites Consortium (AFCC) effort supported by this $5.5M DARPA/AFOSR program under S. Wu and W. Smith

Background

Micromechanics, Properties, Concepts

- Hagood and Bent, "Development of Piezoelectric Fiber Composites for Structural Actuation", *34th AIAA SDM Conference, La Holla, CA, #93-1717*
- Bent and Hagood, "Piezoelectric Fiber Composites with Interdigitated Electrodes", *J. Int. Mat'ls Sys & Str., 8-11, Nov 1997, (also SPIE, 1995, #2441-50)*

Characterization, Strength

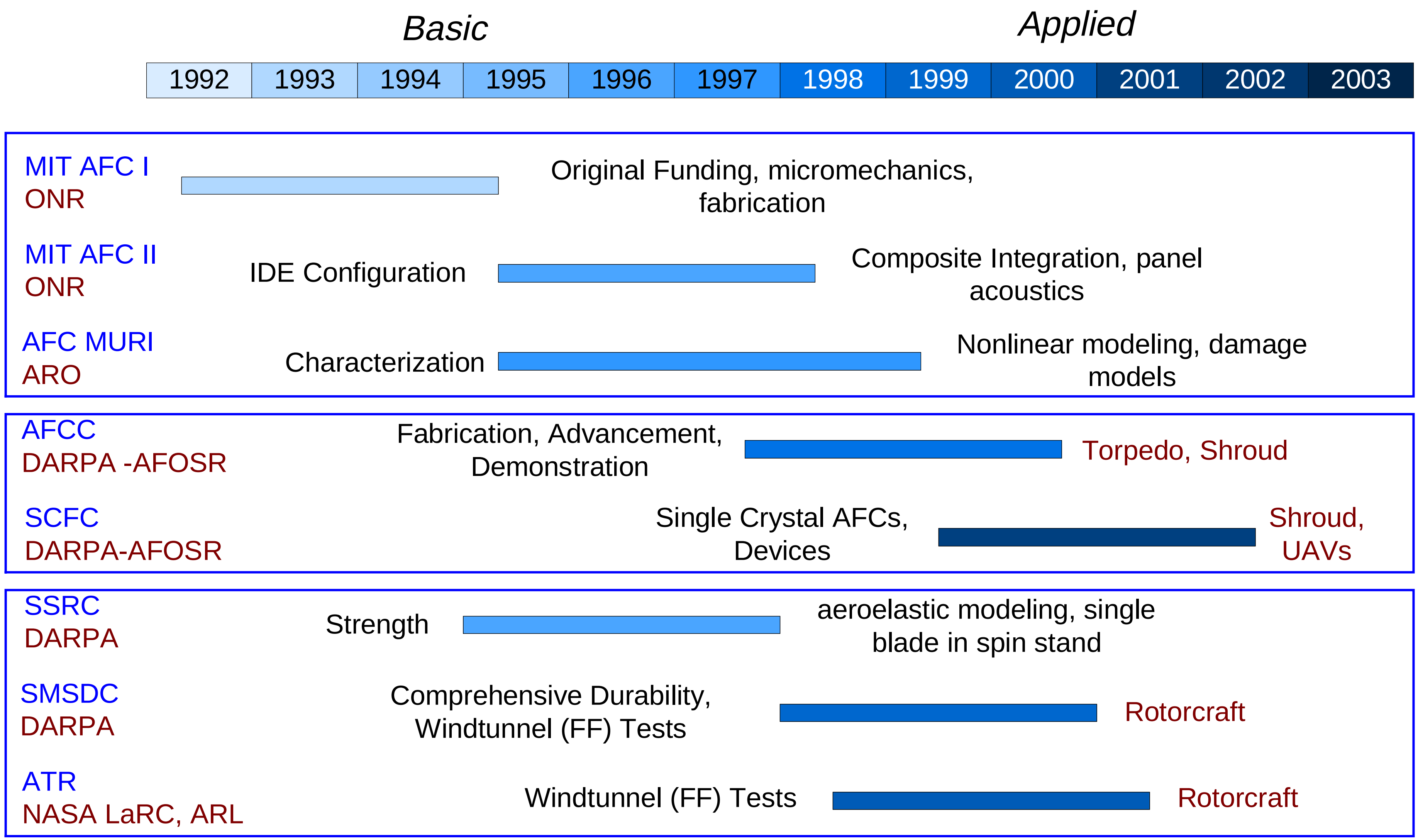
- Rodgers, Bent, and Hagood, "Characterization of Interdigitated Electrode Piezoelectric Fiber Composites for High Electrical and Mechanical Load", *SPIE 1996, # 2717-60*
- Hagood and Pizzochero, "Residual Stiffness and Actuation Properties of Piezoelectric Composites: Theory and Experiment", *J. Int. Mat'ls Sys & Str., Vol. 8, 724-737, Sep 1997, (also ICAST, 1996)*

Rotorcraft Investigations

- Rodgers, Hagood and Weems, "Design and Manufacture of an Integral Twist-Actuated Rotor Blade", *38th AIAA SDM Conference, Kissimmee, FL, #97-1264*
- Derham and Hagood, "Rotor Design Using Smart Materials to Actively Twist Blades", *Amer. Helicopter Soc. 52nd Forum, Washington DC, June 1996.*

Plus 6 SPIE 1999 and 7 SPIE 2000 Smart Materials and Structures Papers...

AFC Related Programs - A Review



AFCC Team Structure

- Requirements
- Demonstration

Torpedos and UUV Apps

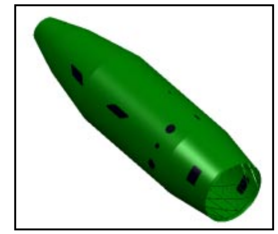
NUWC (D. McDowell)

Packaged Actuator Apps

ACX (S. Yoshikawa)

Payload Shroud and Rotorcraft Apps

Boeing (D. Morris)



AFRL (Kirtland)

Application Requirements

Piezoelectric Composites

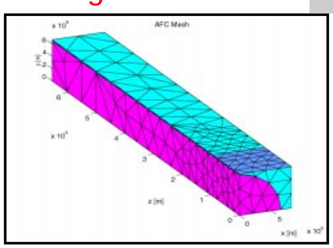
Technology Advancements

- Improved Materials
- Improved Designs

MIT (N. Hagood)

Continuum (A. Bent)

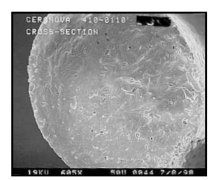
- Low Cost Composite Fabrication
- Improved Designs



Fiber Requirements

Piezoelectric Fibers

CeraNova (M. Pascucci)

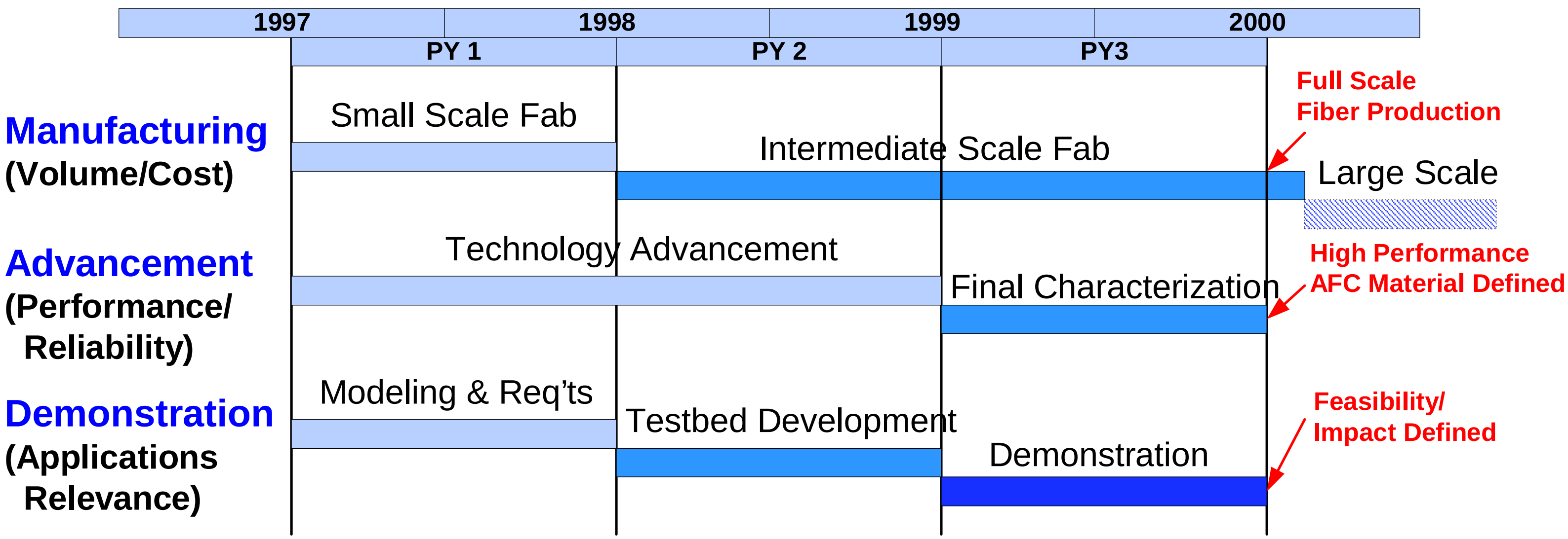


- Low Cost Fiber Fab
- Fiber Processing & QA

Mission & Program Objectives

MISSION: Develop a commercially viable AFC product that is widely accepted and utilized by industry

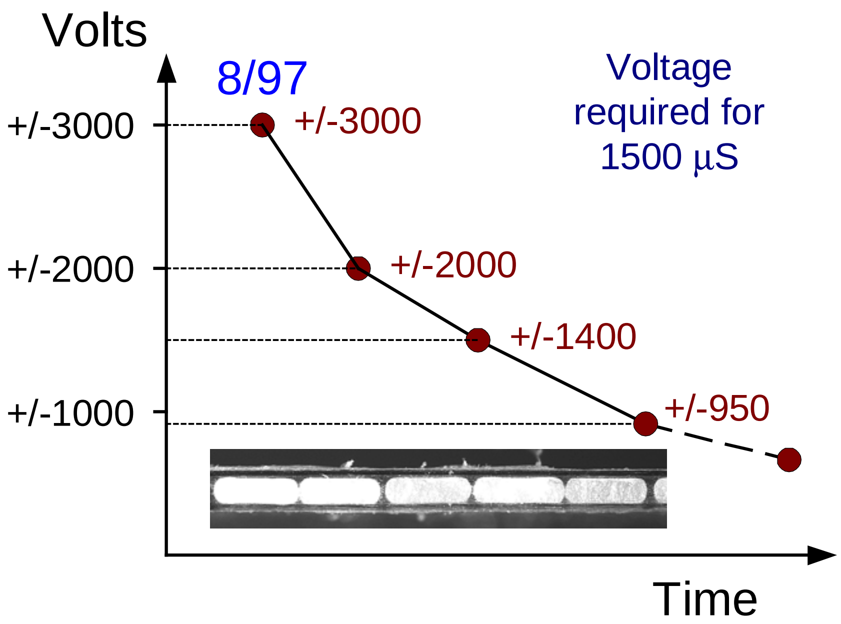
- Fill the actuator role in a number of upcoming applications currently being investigated in multiple programs
- Provide “off the shelf” actuator technology that is demonstrated and proven
- Be available to users at a reasonable cost

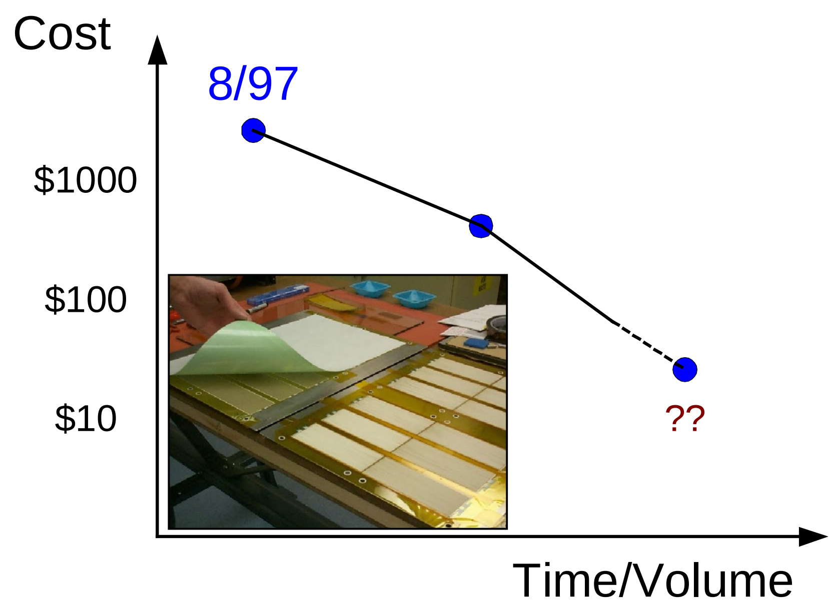


Currently in 34th of originally 36 month program – No Cost extension to 11/00

AFC Technology Improvements

Continuum and its Partners (as a part of DARPA-AFOSR AFCC Program) have made significant advances in AFC Technology





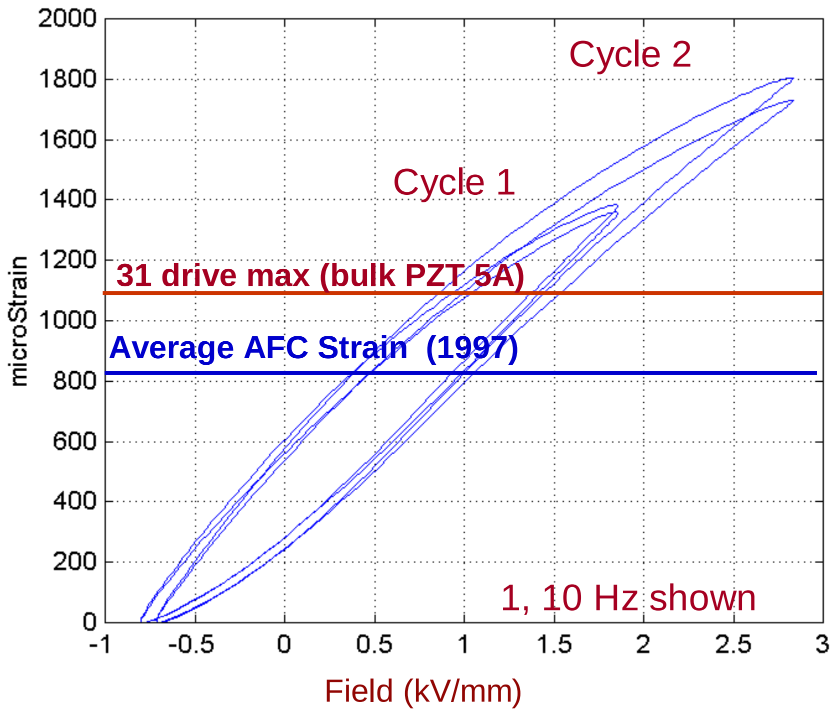
- Process Optimization: semi-automated lamination, fiber mandrel process
- Geometry Optimization: electrode geometry, fiber geometry and diameter
- Material System Optimization: advanced resin and electrode systems

Future: magnetic particle AFCs may offer further improvement…

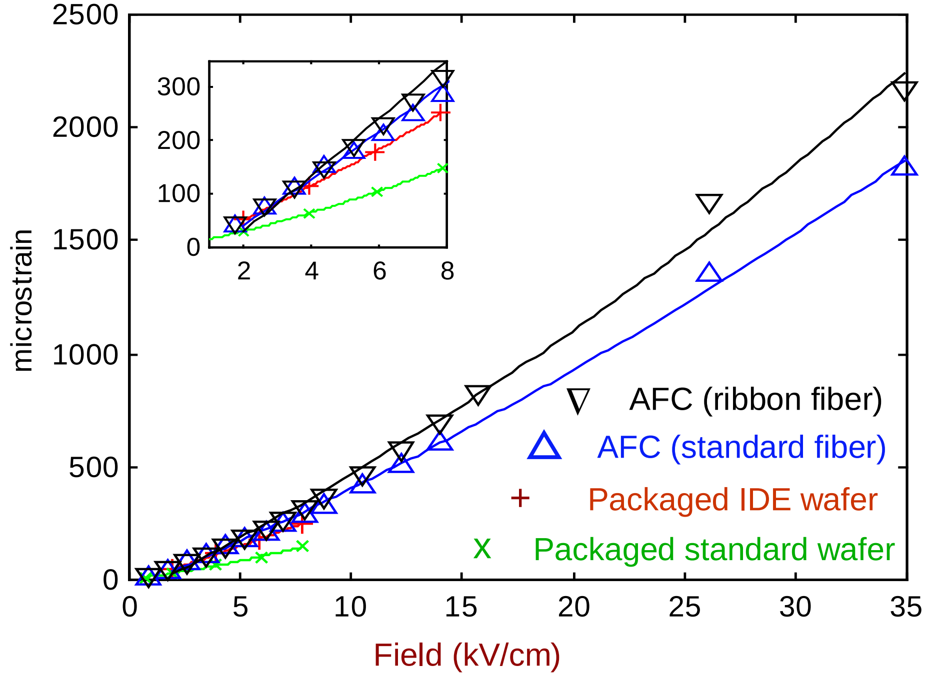
Active Fiber Composite Properties

Advances in materials and processing (developed as part of AFCC) has resulted in 40-60% performance increases from start of program

AFC Improvements



Comparison to Other Actuators

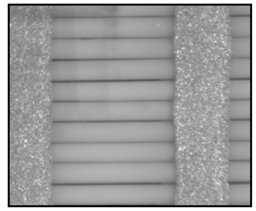


- 33 mode actuators more field efficient (△ ▽ +) than monolithic (31 mode) actuators (x)
- *AFCs have 2 times the strain energy density of a similar 3-1 mode monolithic piezoceramic*

AFC Property Summary - Overview

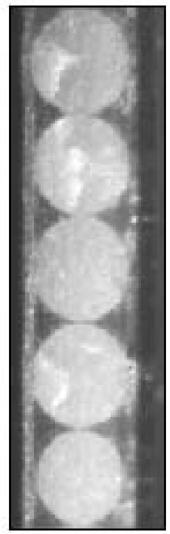
Electrode

Substrate Material	Kapton
Ink	Silver
Thickness (micron)	25.4



Fibers

Type	PZT-5A
Density (g/cm3)	7.8
Diameter (micron)	250



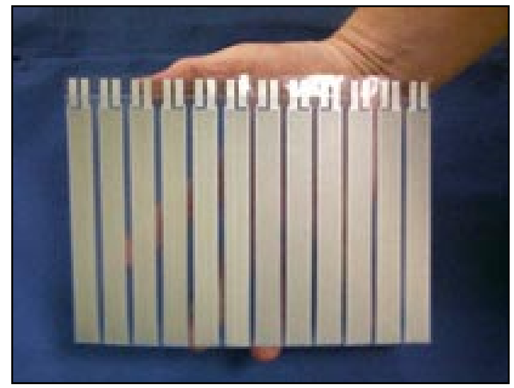
AFC Geometry

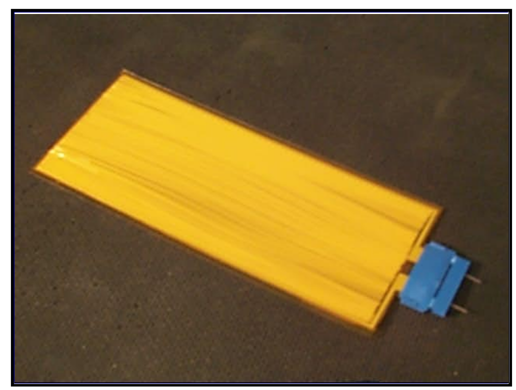
Thickness (micron)	213.6
Overall Area (cm2)	80
Active Area (cm2)	63
Line Fraction	85-90%
Weight (+Cu Tabs) (g)	11.8
Density (Kg/m3)	4500
Areal Density (Kg/m2)	1.55

Characterization

Average Actuation Strain (microS, 3kVpp, 600Vdc)	1200
Operational Voltage Limits	-1500 to 2800
s_{33} (m^2/N)	4.00E-11
s_{13} (m^2/N)	-1.10E-11
s_{11} (m^2/N)	6.00E-11
d_{33} (m/V)	1.50E-10
K_{33}	495

STANDARD AFC



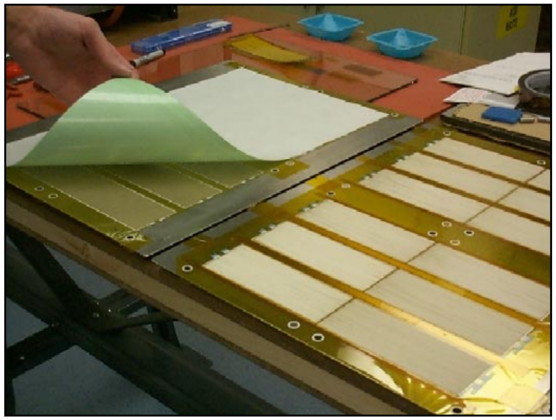


Medium Scale - Lamination Technology

- *Innovations in materials and fabrication processes have drastically reduced part cycle times, improved performance and uniformity*
- Technology-ready for volumes of 100,000's per year
- All approaches scalable to *high* volume production, using roll-to-roll

Materials & Tooling

- Film Resin approaches
- Precision alignment & tool
- New electrode technology



Lamination Press Cure

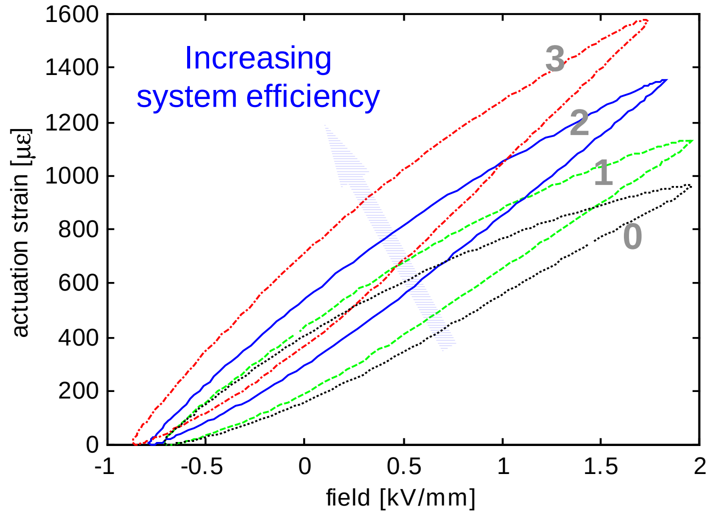
- Lamination technology
- Process: Time, pressure, vacuum, temperature

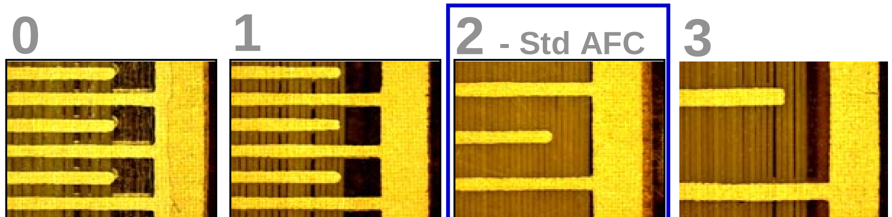
Post-Cure & QA

- Full sheet techniques
- Automated poling, QA testing, and data logging

AFC Architecture - Overview

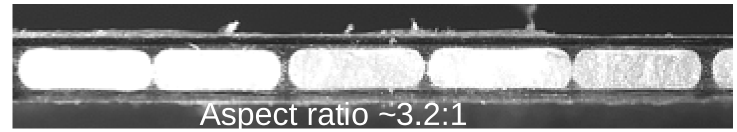
Electrode & fiber geometry offer clear tradeoffs in voltage, authority & efficiency



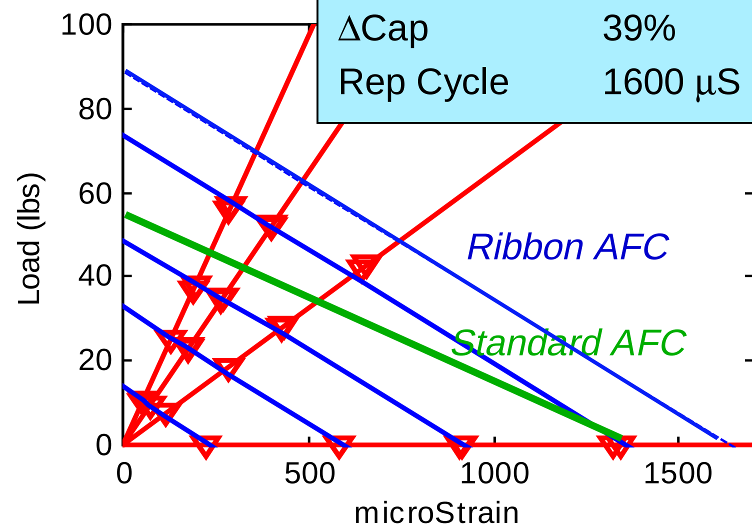


0	1	2 - Std AFC	3
Large fiber, 25 mil pitch p/h=2.7	Small fiber, 25 mil pitch p/h=4.6	Small fiber, 45 mil pitch p/h=8.3	Small fiber, 90 mil pitch p/h=16.7

p = pitch, h = fiber diameter



Fraction, v_f	72%
coupling, k_{33}	0.60
ΔCap	39%
Rep Cycle	1600 μS



Future ribbon configuration provides enhanced free strain and blocked force

AFC architecture flexibility provides design envelope for customer

CeraNova - MicroRod™ Technology

PZT fiber is core to success of AFC Technology: Cost, Volume, Quality

- Apply extrusion technology as the basis for forming fine PZT (85-250 µm) fibers

Development Goals:

- Cost Reduction: factor of 10x
- Volume: from 16 km/yr to 920 km/yr

Fiber Process Flow

Mixing
- PZT Powders
- Binder Formulations
- Mixing Methods

↓

Extrusion
- Die Design
- Temperature, Pressure
- Draw Down

↓

Green Fiber Handling
- Single Fiber or Multi-Fiber Handling
- Mandrel Unit Handling

↓

Firing (BBO & Sinter)
- Time, Temp, Air Flow
- Micro-atmosphere control
- Powder Reactivity

↓

QA
- Single Fiber dielectric or remnant polarization
- 1-3 composite testing

Fiber Process Monitoring & Control

Process improvements have resulted in fine fiber materials with high piezo-electricity, and uniformity in diameter and straightness

Challenge: fine features, PZT difficult to process, high sensitivity

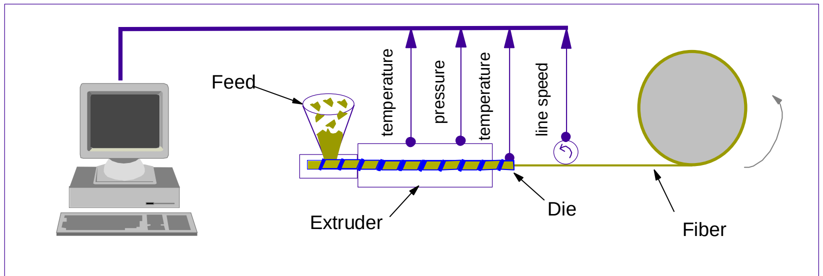
Approach: focus on green fiber extrusion technology, diameter control, micro-atmosphere sintering

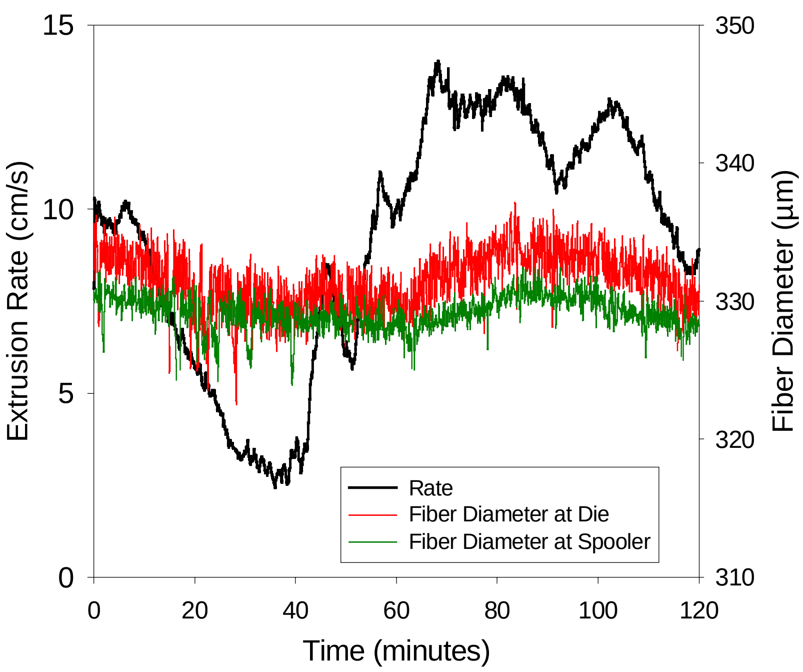
- Installation of PC-based extrusion monitoring capability
- Closed loop control for extrusion die temperature
- Real-time laser diffraction measure for fiber diameter

Results:

- Control of lead-loss
- Tighter dimensional tolerances
- Improved uniformity of electro-mechanical properties

Properties approaching bulk ceramic



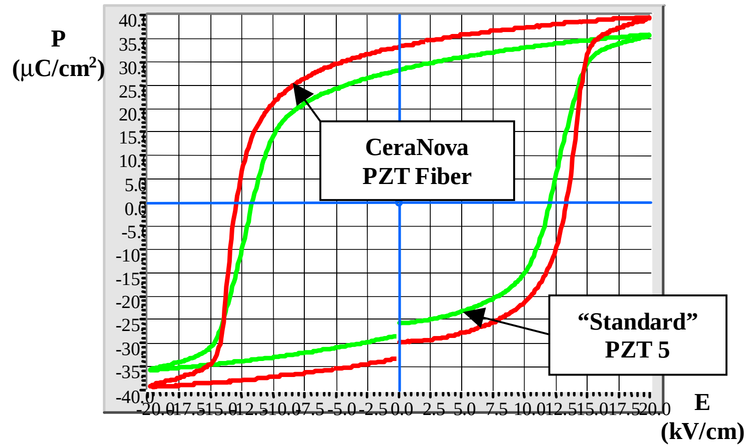


Fiber Properties & QA

Establishing fiber QC is an integral aspect of process improvment and monitoring product used in AFC

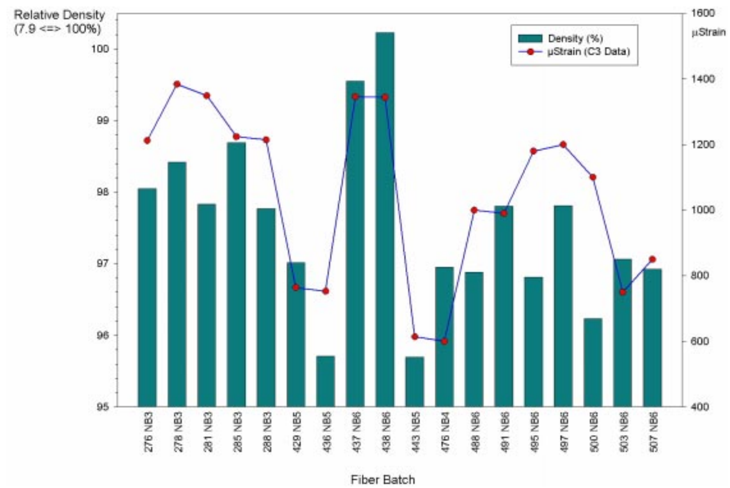
Challenges:

- Fine features of fiber make very difficult
- Relating measurement to process steps
- Correlating metric to AFC performance



Approach:

- Standard Tools: TGA, XRD, SEM, etc.
- Development of single fiber Remnant Polarization (P-E loop) test (with PSU)
  - P_r, E_c, loop shape
- Fiber Density measurement
  - Strong AFC strain correlation
  - Properties very sensitive to porosity



Result:

- Quantified QA metric correlation for use in production

Fiber Preforms/Volume & Handling

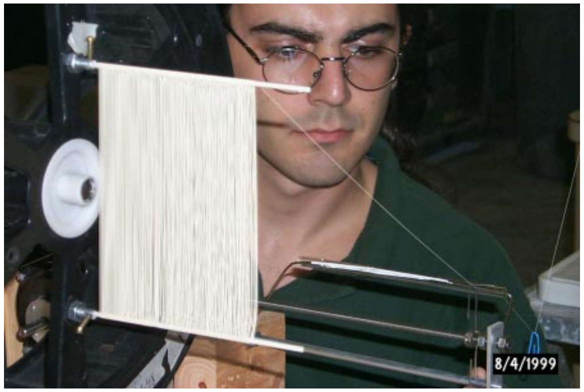
Handling fibers in an automated and "bulk" manner critical to achieving cost and volume goals

Challenges:

- Process for high quality fiber "preforms" – single fiber unit
- Maintaining fiber geometry, straightness, properties

Approach:

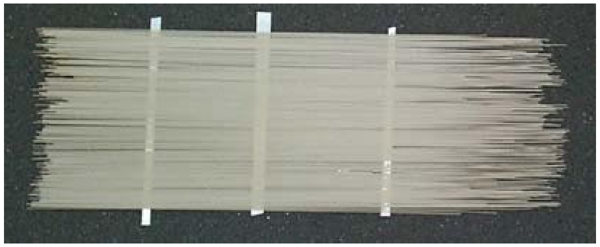
- Mandrel winding process for green fibers on-line (for handling & firing 1000's fibers)



- Sintering challenges
  - Modifications in BBO/sinter to accommodate mandrel, large number of fibers, post-handling

Result:

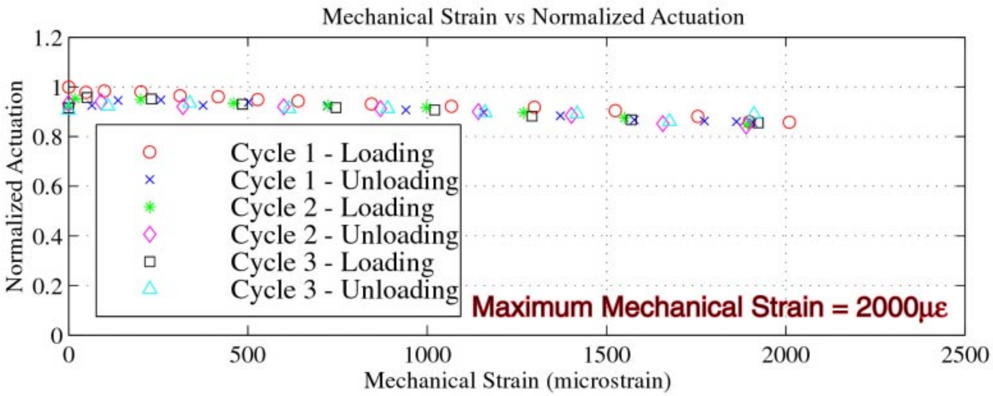
- Control for straight, uniform fibers achieved
- Continuum/CeraNova working on fiber transfer

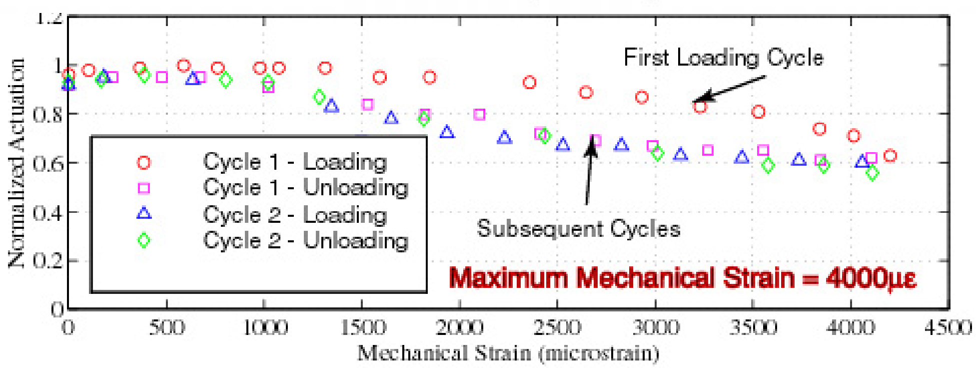


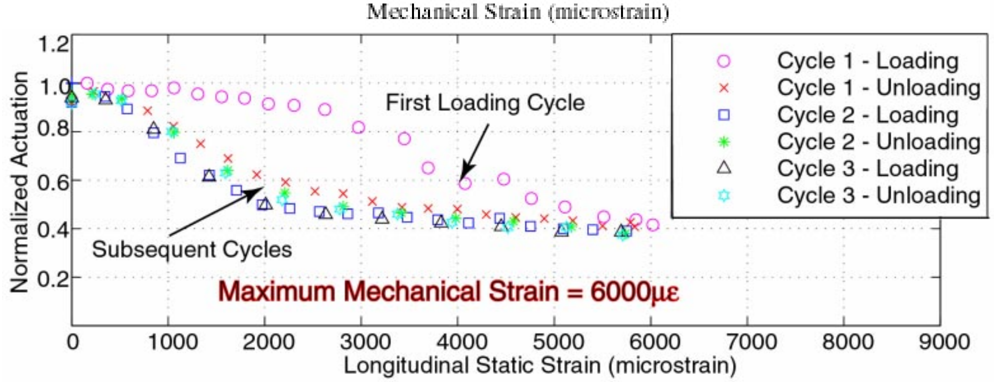
Actuator Robustness

ACTIVE MATERIALS & STRUCTURES LABORATORY

Characterization for high strain environments demonstrate actuator robustness







N.W.Hagood & V.K.Wickramasinghe

- In-situ actuation under high static tensile loads
  - AFC actuated at 4000Vpp cycle
  - Laminated with 0°/90° E-Glass
- Continued operation up to 8000 microstrain
- Nearly full recovery of residual properties at higher peak strain loading

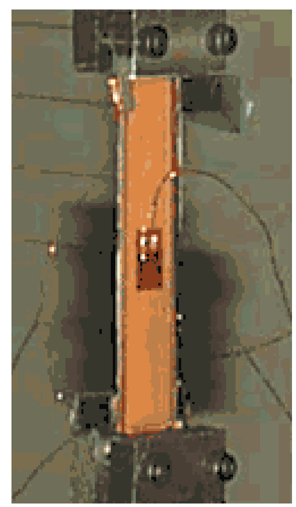


Illustration of E-glass laminated AFC gripped for actuation under load tests (Pizzochero & Hagood, 1996)

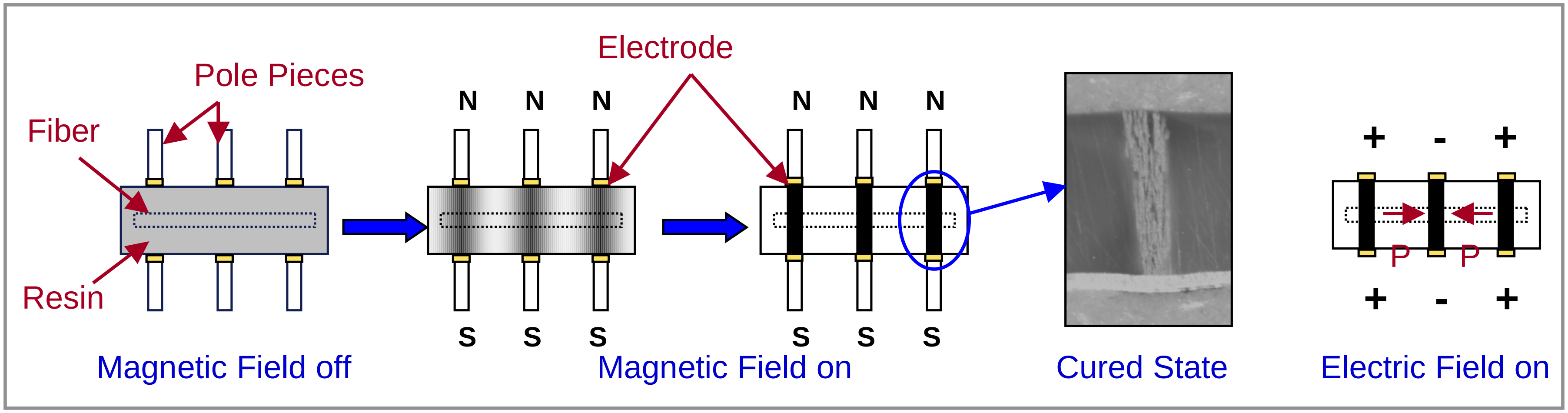
Anisotropically Aligned Particle Doping

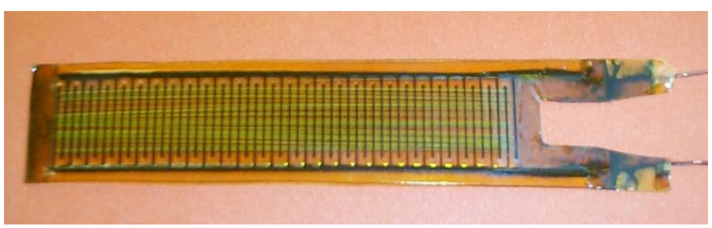
ACTIVE MATERIALS & STRUCTURES LABORATORY

Anisotropic alignment of conductive particles provides advantages in AFCs

Lower voltage *reduced processing sensitivity* *reinforcements possible*

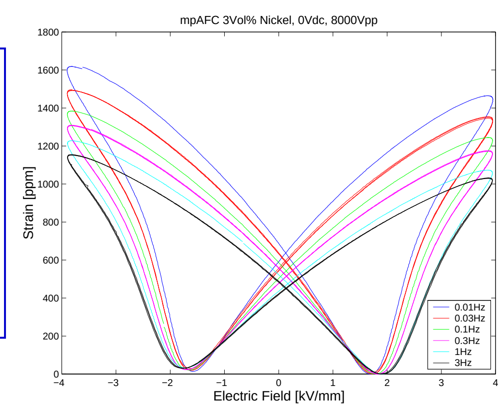
1. Doping of resin with ferromagnetic, electrically conductive metallic particles
2. Controlled alignment of particles in resin using magnetic field during fab





1. Electrode-less magnetic particle AFC

2. Ferromagnetic particles create direct path to fibers - High strains possible with large electrode to fiber gap



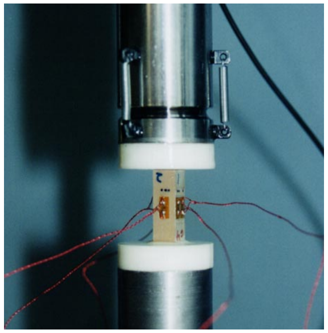
N.W.Hagood & B. Janos

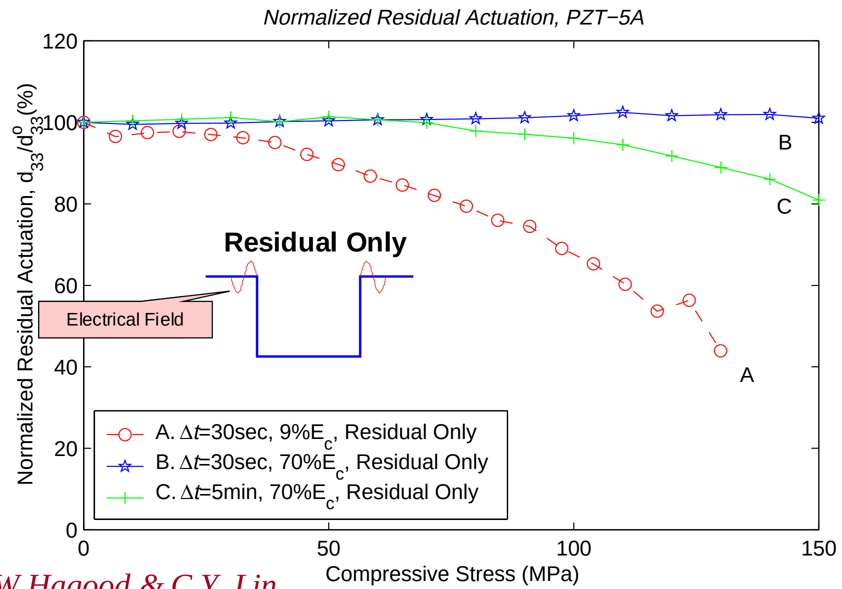
Materials & AFC Modeling

ACTIVE MATERIALS & STRUCTURES LABORATORY

Examine 33 mode of actuation susceptibility to compressive stress

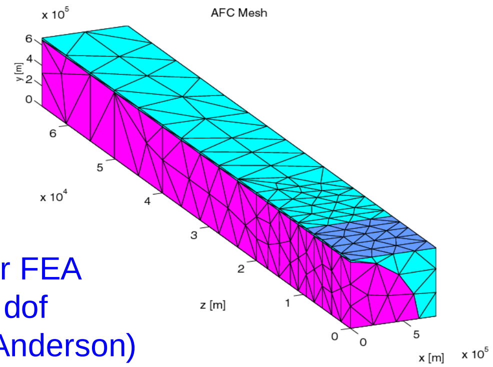
- Bulk Materials
  - Stress-field-time effects
  - Material model inputs
- AFCs
  - Remarkable resistance to depoling



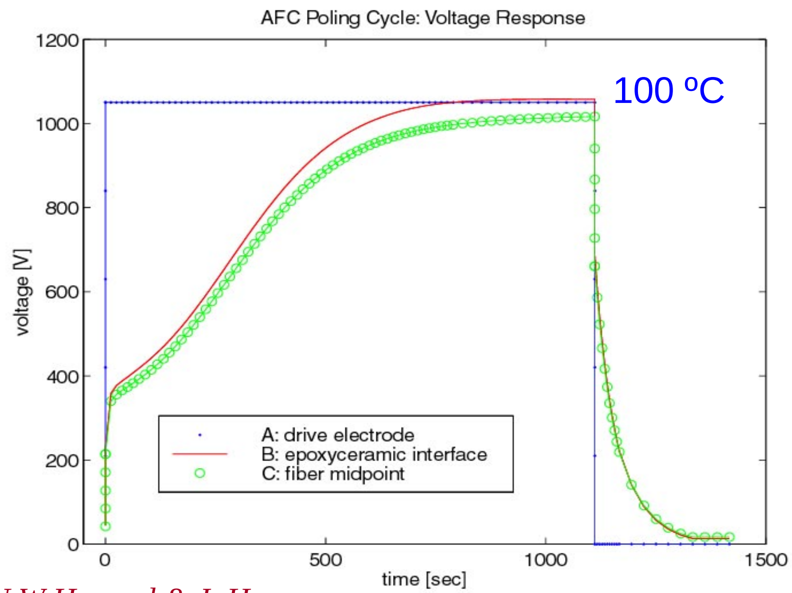


N.W.Hagood & C.Y. Lin

Understanding transient effects using 3D nonlinear FEA models - conductivity



MIT Nonlinear FEA
Hybrid u-V-D dof
ARO MURI (Anderson)



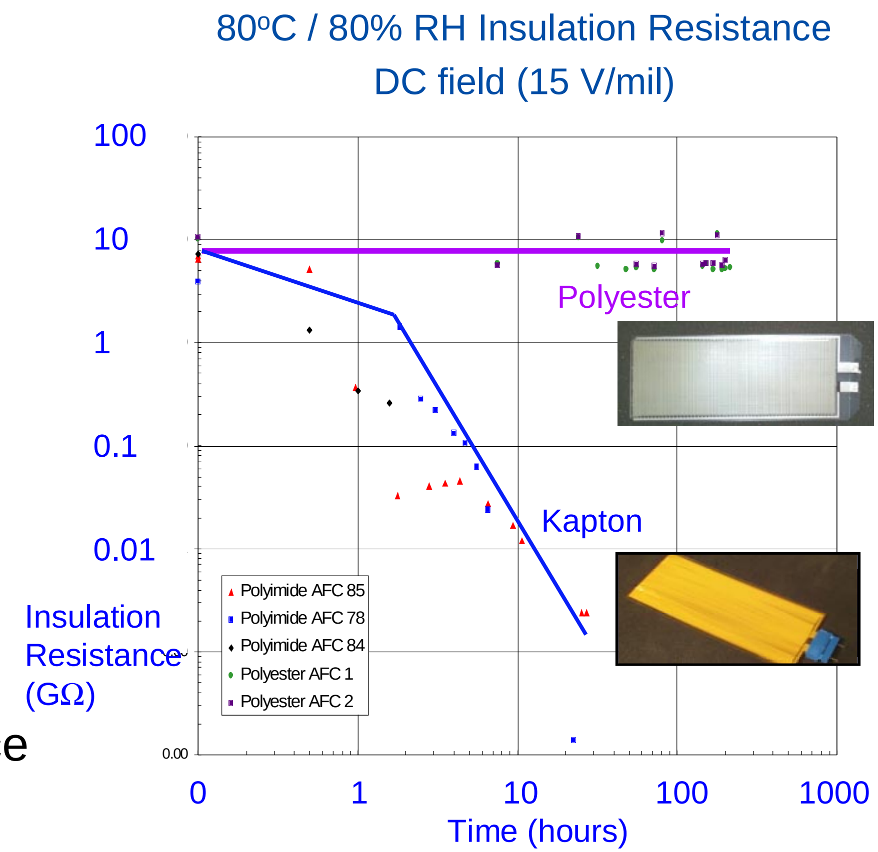
N.W.Hagood & J. Harper

Environmental Tests

Environmental testing demonstrates that careful choice of materials can offer enhanced actuator properties for specific applications

Series of Environmental testing

- Examining extreme heat/humidity conditions (80/80) under DC voltage
  - AFCs, wafers, IDE wafers
- Issues:
  - Silver migration: DC voltage
  - Absorption: Kapton, IDE geometry
- Developed new electrode system:
  - Low cost
  - Superior resistance & recovery
  - Maintained properties & performance of Kapton

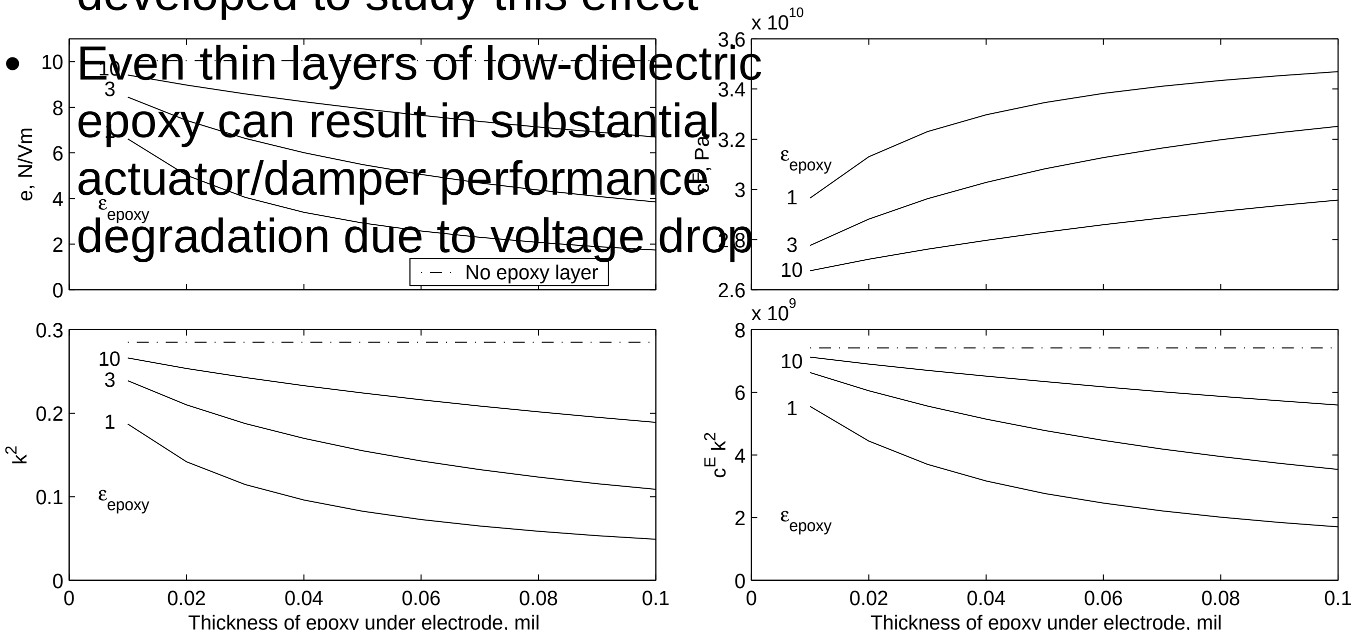


Direct Electrode-Ceramic Contact

Work with PZT wafers helps to understand impact of IDE™-type devices

Non-ohmic contact results from epoxy separation between electrode/ceramic

- Quasi-2D FEA model was developed to study this effect
- Even thin layers of low-dielectric epoxy can result in substantial actuator/damper performance degradation due to voltage drop



D.J. Warkentin

Problems with direct electrode-ceramic contact confirmed with wafers

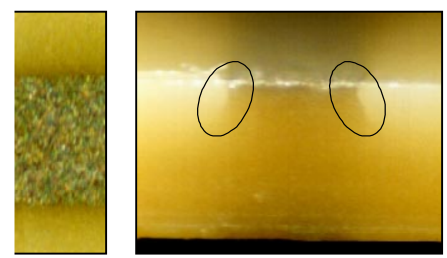
- Electrode pattern formed directly on ceramic surface by etching

ully poled

ion at field

n numerous

e edges



AFCs rely on slight non-ohmic contact to provide damage resistance and damage tolerance – well worth the additional voltage

Applications Support & Demonstration

Individual Blade Control

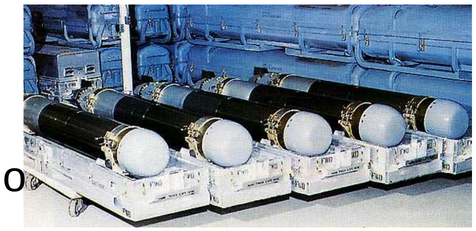
(Boeing, NASA, ARL)
Target Vehicle:
CH47D, others

Objective:

- integral AFC actuators for dynamic twist control (IBC)

Torpedo Silencing

(NAVSEA, ONR)
Target Vehicle:
Heavy-weight torpedo



Objective:

- reduce radiated noise of torpedoes and UUVs

Payload Shroud

(Boeing)
Target Vehicle:
SeaLaunch,
Minotaur

Objective:

- structural-acoustic control to reduce noise transmission

Twin-Tail Military Aircraft

(NASA, AFRL, Boeing)
Target Vehicle:
F-18, F-22

Objective:

- active control to minimize tail buffet response

Composite Integration & Test

Examining feasibility of AFCs in large scale aerospace applications through system design studies, sub-component manufacturing, and demonstrations

In-Situ Testing

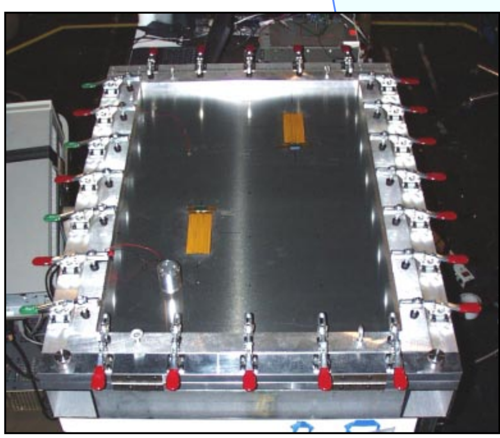
Electrical fatigue
Lap shear/peel tests
Compressive stress depole

Impact Studies

Manufacturing Impact
Acoustic Attenuation
AFC Requirements
Cost, Weight

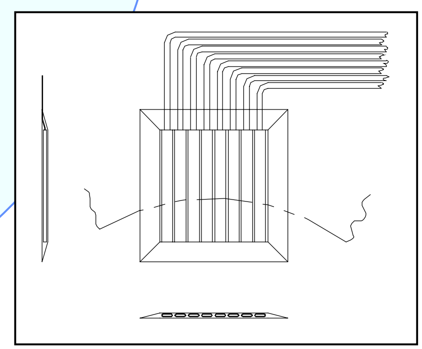
Building a core competency for working with AFC materials

Scaled Demonstration



Passive/Active Control Demo
Structural-Acoustic models
Model Validation

Integration Issues



Custom connectors
Connections fatigue
Composite Lay-up & Cure

PHANTOM WORKS

Demonstration - Shroud Feasibility

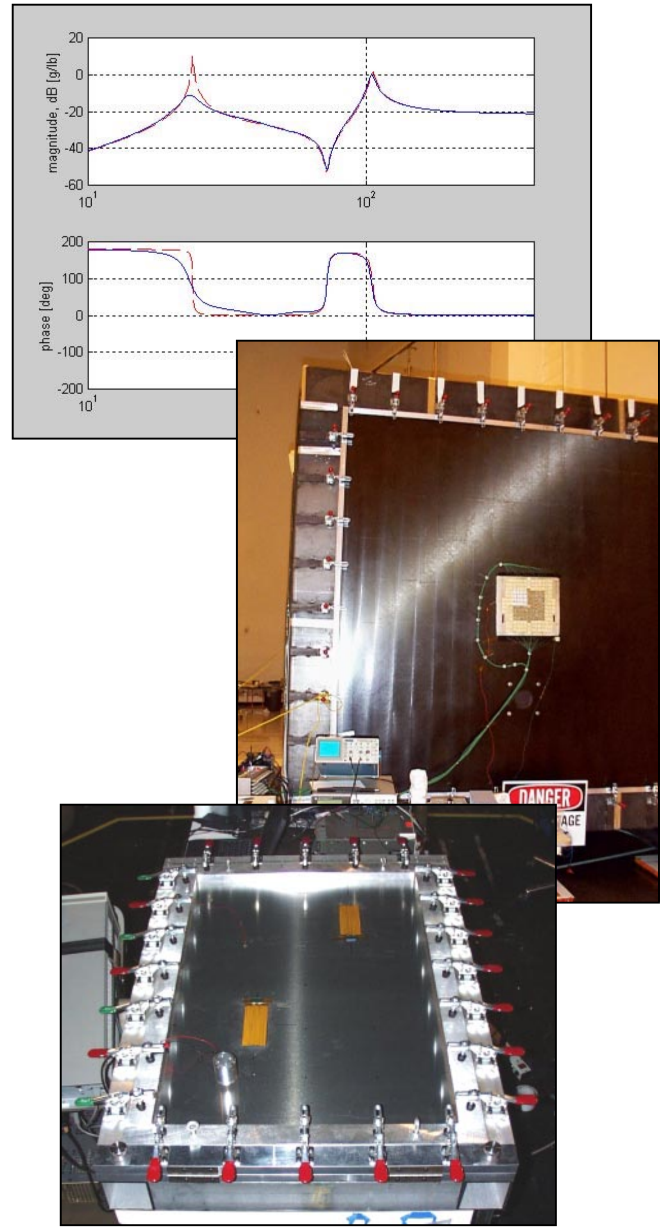
BOEING

Determine feasibility of AFCs in shroud transmission attenuation

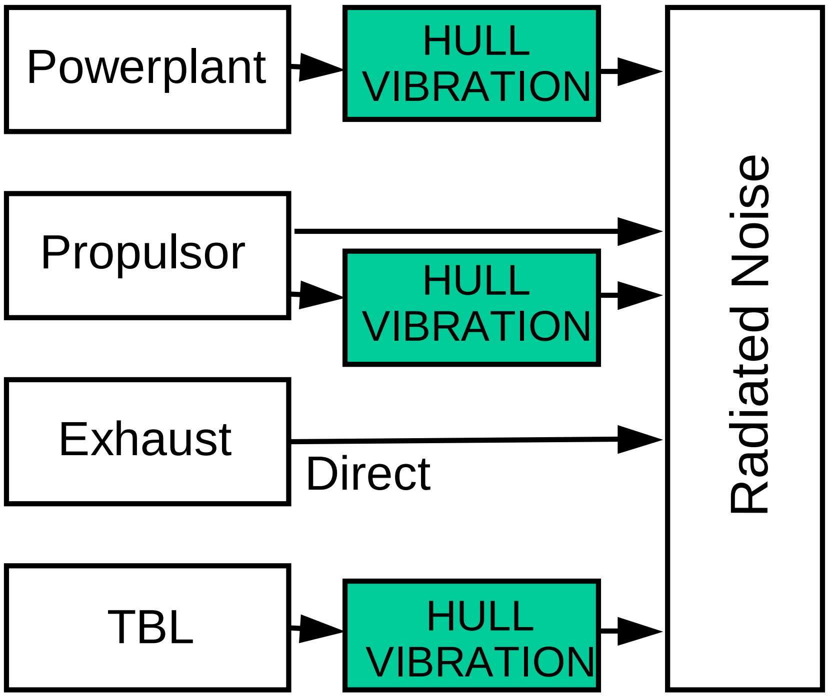
Opportunity for improvements in cost, weight, and performance over existing passive treatment

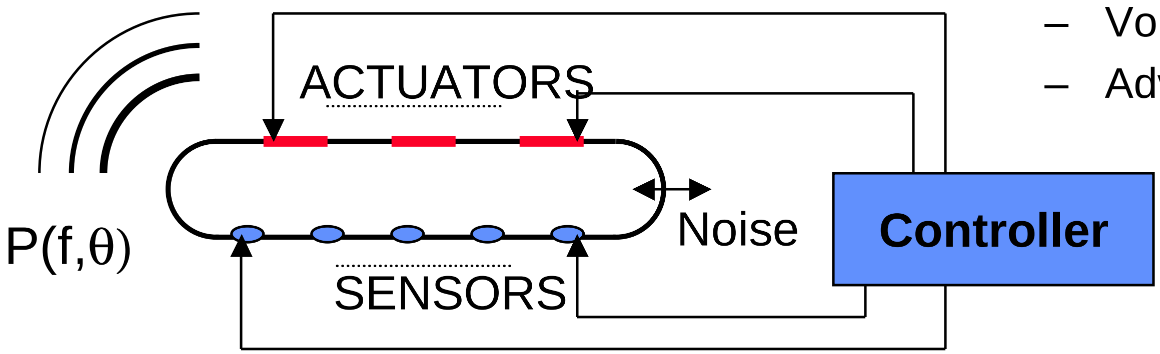
Approach:

- Successful demonstration of PZT wafers on 9' panel testbed (1.6% coverage)
  - model/experiment closed loop validation
  - 20 dB attenuation in 1st critical mode
- Acoustic component of SeaLaunch coupled model near completion
  - tools available to assess full scale feasibility
- Completion of composite panel testbed
  - AFCs integrated into shroud skin panels
  - Comparison of control approaches: passive, classical, LQG, LMS feedforward



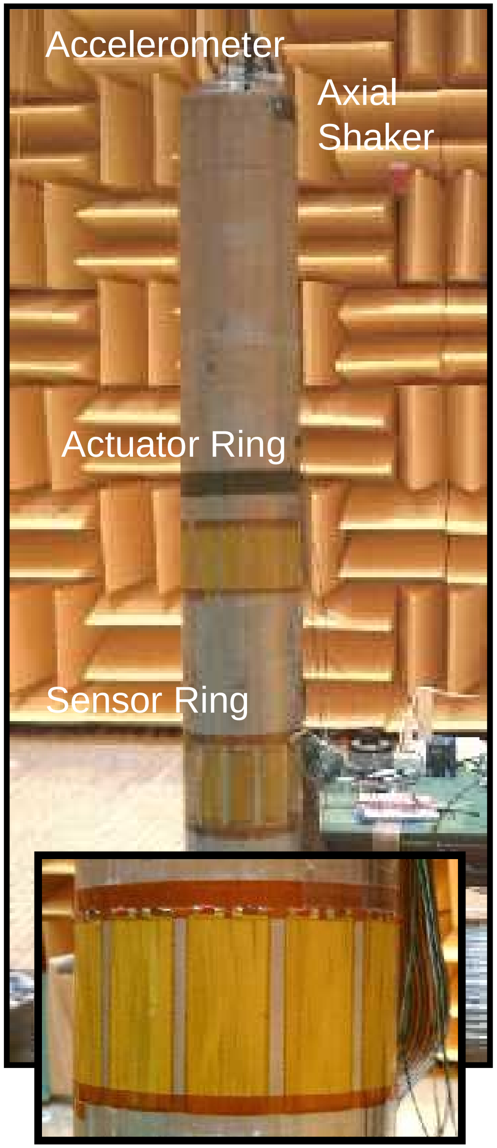
Torpedo Application





- Feasibility
  - Approach to controlling noise
  - Actuator authority
- Control Architecture
  - Feedforward v. Feedback
  - Tonal v. Broadband
  - Number of Actuators
  - Number of Sensors
  - Actuator & Sensor Placement
- System Level Design
  - Electronic requirements
  - Damage tolerance
  - Volume Requirements
  - Adverse Material Exposures

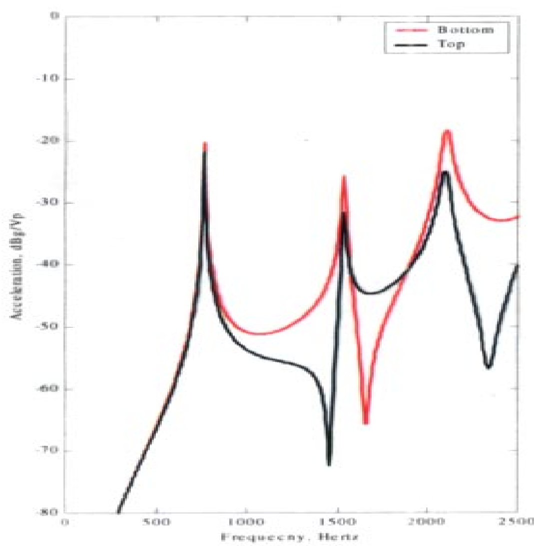
Modeling Drive Authority



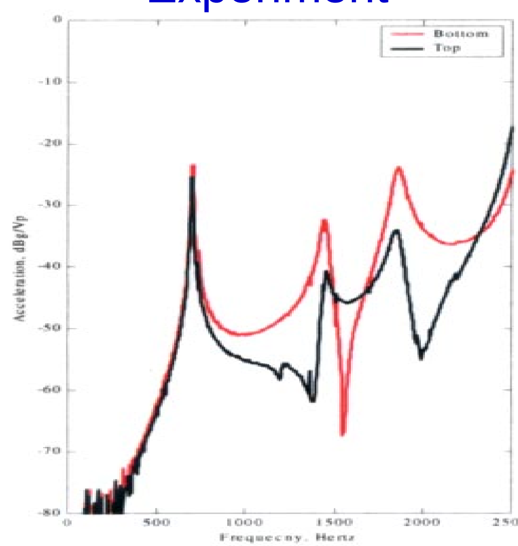
Developed and validated approach to AFC control of radiated noise using torpedo testbed

- *Axisymmetric FEA including shell, endcaps, acoustic fluid and anisotropic AFC actuators*
- *Model-experiment validation: drive authority transfer functions*

Model



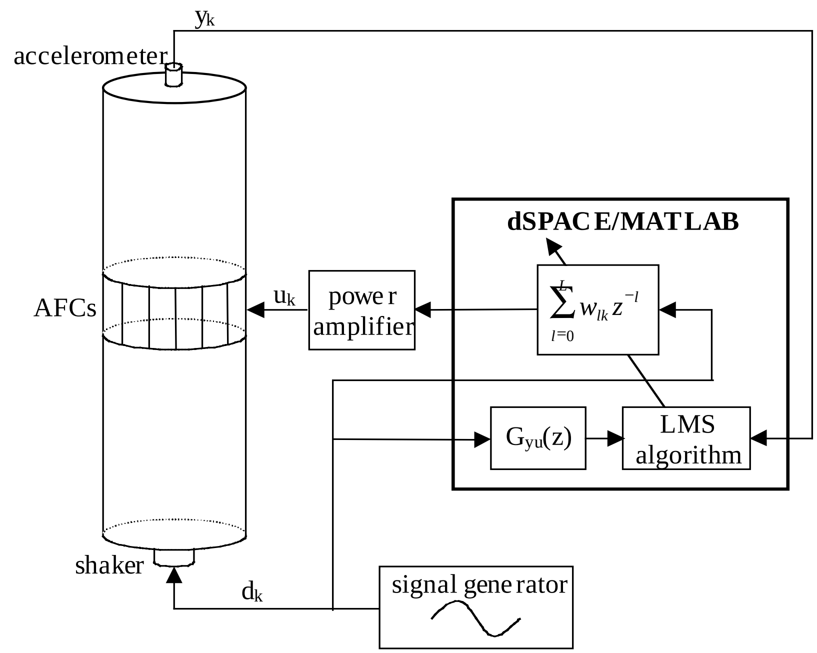
Experiment



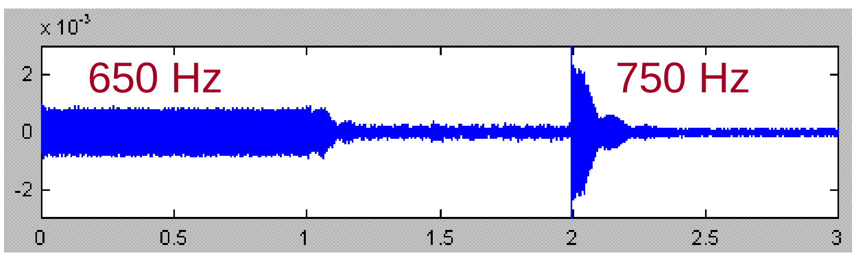
Control Demonstration – Tone Tracking

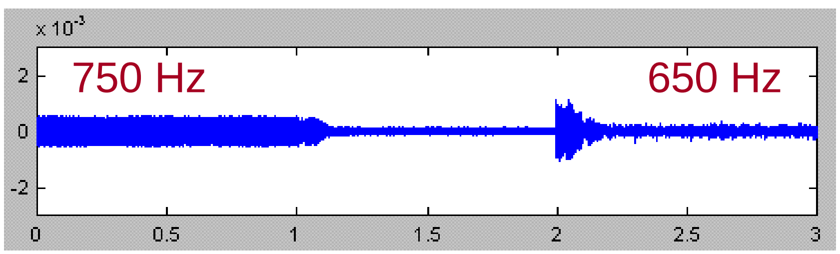
Successfully demonstrated adaptive control of cylindrical shell vibration/acoustic radiation

- Feedforward LMS control
- Multiple tone and tone tracking demonstration
- 25-30 dB reduction in realistic hull vibration levels with 20-40 volts on AFCs



Application of validated modeling approach to full scale torpedo designs show that AFCs will have authority necessary

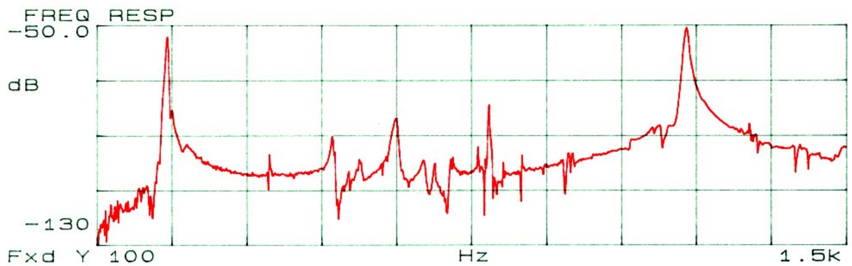




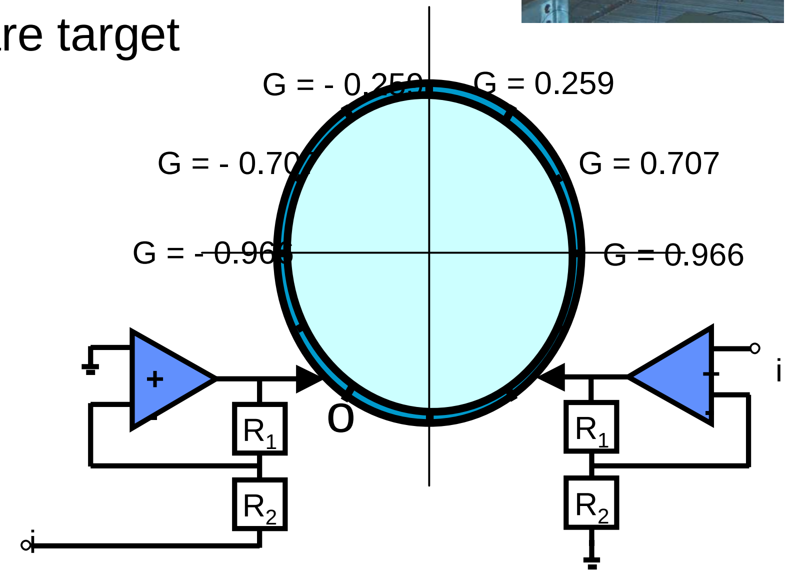
Follow-On Effort

Follow-On efforts demonstrate AFC system for full torpedo

- System Modeling & Design
  - ID of shell dynamics, actuator placement models, develop amplifier requirements
  - Optimal AFC design (voltage, authority, etc), AFC package & connections, humidity protection
- In-Air demonstration
  - Anechoic chamber; demonstrate entire system
- In-Water: acoustic holography for far-field noise (NRL)
- Future: At-sea trials with fleet hardware are target demonstration in 2-3 years



Exploiting the AFC anisotropy and segmenting for modal sensing and control (driving n=0,1; sensing n=0,1,2,3…)



Task II Active Materials Rotor Team Members And Key Interactions

MIT AMSL

BOEING

AMR Core Team

Ephrahim Garcia — *Program sponsor*

Philadelphia

Bob Derham - P. I.
Doug Weems
Rich Bussom
M. Bobby Mathew

Requirements and coordination . Rotor system design, testing and interpretation.

Seattle

Dean Jacot
Mike Gamble

Electronics Design Fab. & Integration

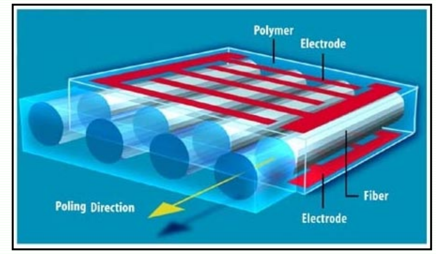
MIT AMSL

Active Matl. Structures Lab

Nesbitt Hagood
Viresh Wickramasinghe
Mads Schmidt

Material System Characterizations. Risk reduction testing and analysis

Reqmts



AFCC Program (A. Bent)

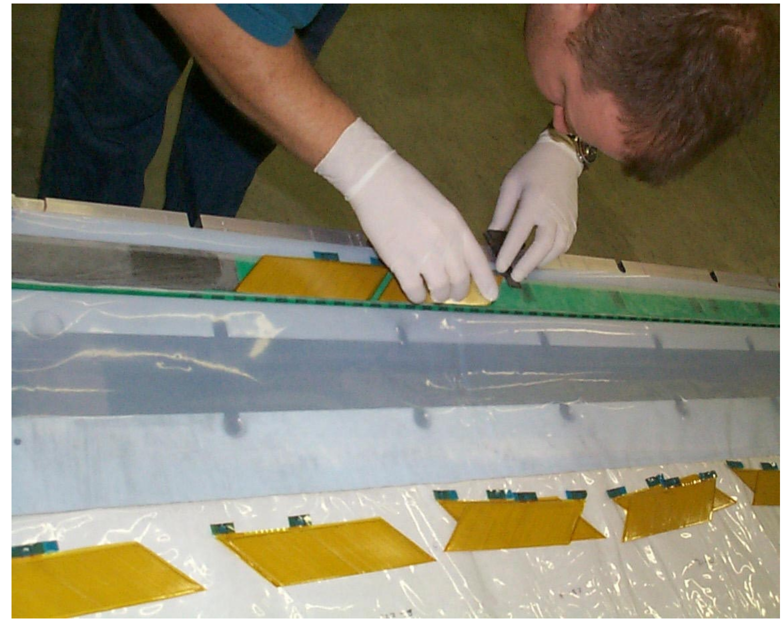
C3 : pre-production AFC lamina capability
CeraNova: PZT fiber production capability
ACX: pre-production packaging capability
MIT: materials technology to final form
Boeing/NUWC: application demos of AFCs

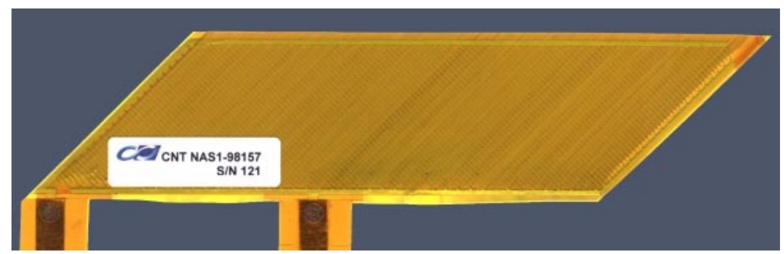
ATR Program (M. Wilbur)

MIT (C. Cesnick), NASA & Army LaRC

1. Develop generic research model for low-stress demo AFC blade
2. Intermediate AFC design iteration
3. Conduct Test(s) in Heavy gas TDT

NASA LaRC ATR Program





Program

- NASA Active Twist Rotor (ATR) program
  - Matt Wilbur, LaRC PI
  - Modeling and Design, MIT, C. Cesnik
- Objective: forward flight in TDT

Demonstration

- 5 blades, 24 AFCs/blade
- showcase for new standard AFC

Continuum Involvement

- AFC design and manufacture
  - NASA contract for actual AFC fabrication (Continuum, CeraNova)
- Integration support (Dec 99)
  - blade fabrication conducted by ATI
- Test support, ongoing

- 1/6th scale LaRC designed blade
- 120 AFC 45 degree packs
  - ~2” by 6” long, 1106 μS average

LaRC Model F-18 Tail

Objectives:

- Follow-on work by B. Moses as part of ACROBAT program
  - Examine control authority, robustness of AFC materials

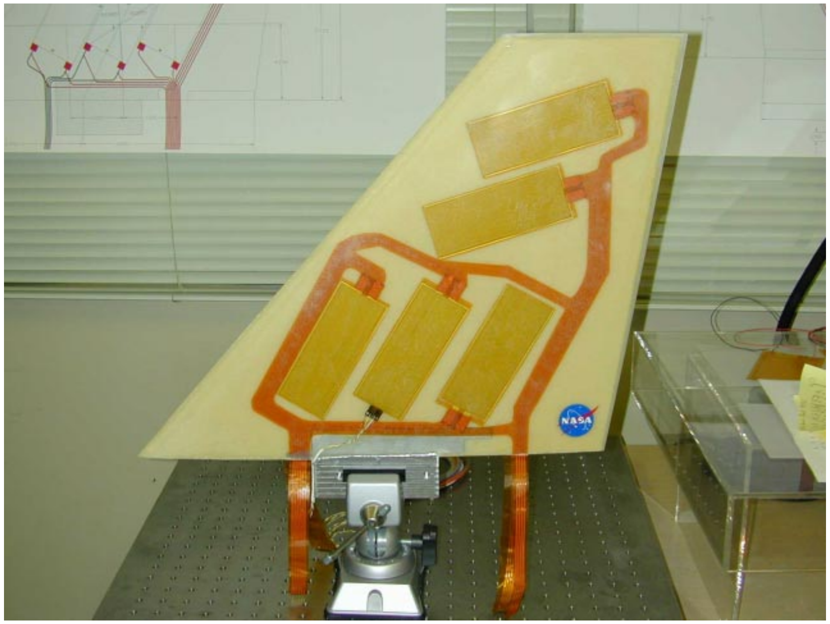
Tests:

- NASA LaRC TDT
  - Check-out, Feb 2000
  - Testing: March-April 2000

Interactions:

- Completing Phase I SBIR in Twin-Tail Buffet for AFCs and high efficiency electronics
- Subject of ASME Paper 10/00
- Follow-on Twin-tail program still being defined (flight in '02-'03)

Photograph courtesy of K. Wilkie, B. Moses, NASA LaRC



- 1/6th scale sting-mounted tail F-18 model
- 10 AFCs (5/side), 2"x5", large diam
  - New standard AFCs
- Average Strain: 1214 μS
- Total Weight: 3.6 ounces

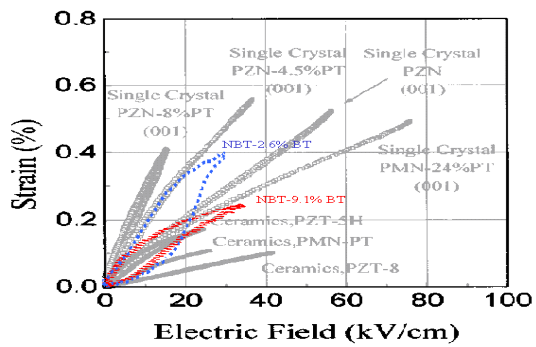
What's Next? …*Single-Crystal AFC's*

Single-Crystal Data:
Park and Shrout (1997)
Y.-M. Chiang (1999)

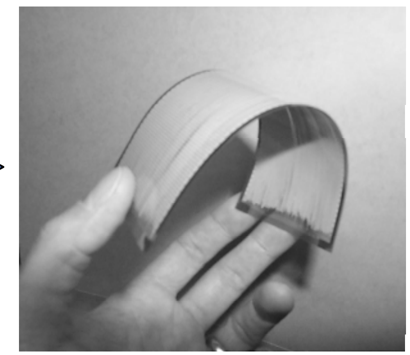
Pb-Based Crystal

NBT-Based Crystal

Exploit



Translate



Can exploit the intrinsic materials properties of single crystal piezoelectrics to real device applications through AFCs

- *High coupling; large d33; high anhysteretic strains*

Fiber Composite architecture offers distinct advantages for the application of single crystal materials

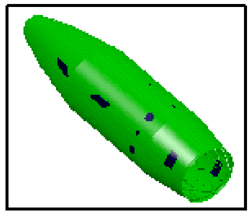
- *Tolerance of flaws and texture; low cost, conformable, large area scAFCs*

Single Crystal Fiber Composite (SCFC) Program

- Boeing
- MIT

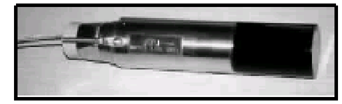
Applications

Payload Shroud



UCAVs

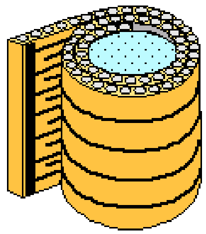
Transducers



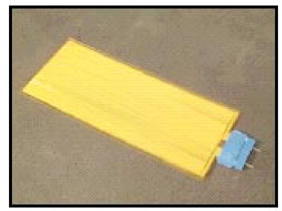
Other Possible Drop-In Applications

- Continuum

Composites & Composite Devices



AFC Stacks (Out-of-Plane)



AFCs (In-Plane)

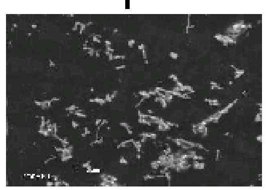
- MIT
- Saphikon
- CeraNova
- Advanced Cerametrics

Fibers

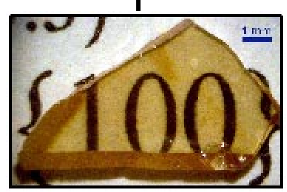
- Single Crystal
- Large Grain
- Textured

- NexTech Materials
- MIT

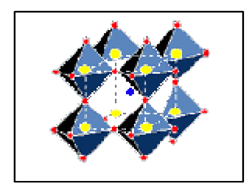
Powder/Seed Compositions



Lead Based Compositions (PMN-PT, Others)



Bismuth Based Compositions (NBT- KBT- BT, Others)



Compositional Design

Single Crystal and Textured Polycrystalline Fibers

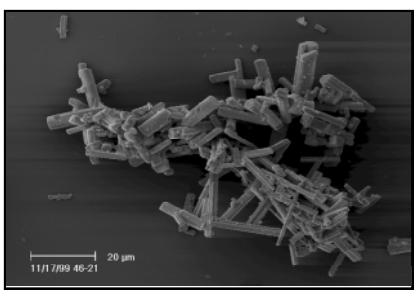
- Materials Systems
  - $(Na_{1/2}Bi_{1/2})TiO_3$ - $BaTiO_3$
  - Co-Doped NBT, Others

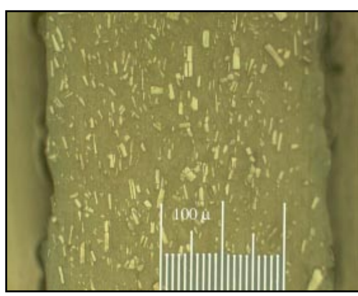
    Chiang, Farrey and Soukhojak (1998)

  - $Pb(Mg_{1/3}Nb_{2/3})O_3$ - $PbTiO_3$

    Nomura, Uchino and Kuwata (1982)

    Park and Shrout (1997)
  - NBT-BT, Co-Doped NBT, Others





NexTech Seeds *CeraNova Green Fiber*

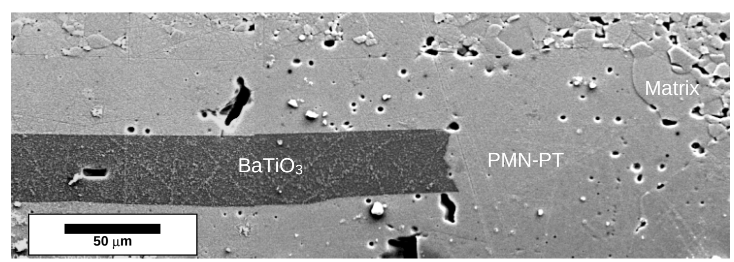
- Attributes / Characteristics

Single-Crystals

  - Congruently melting compositions
  - Growth by flux, Bridgman, and Edge-defined Film techniques
  - Compositional development promises improved properties (anhysteretic strain, dielectric constant)

Textured Polycrystals

  - Pb-based single-crystals show excellent piezo properties
  - Synthesis of seed crystals demonstrated
  - Crystal growth possible by seeded polycrystalline conversion routes



ACTIVE MATERIALS & STRUCTURES LABORATORY

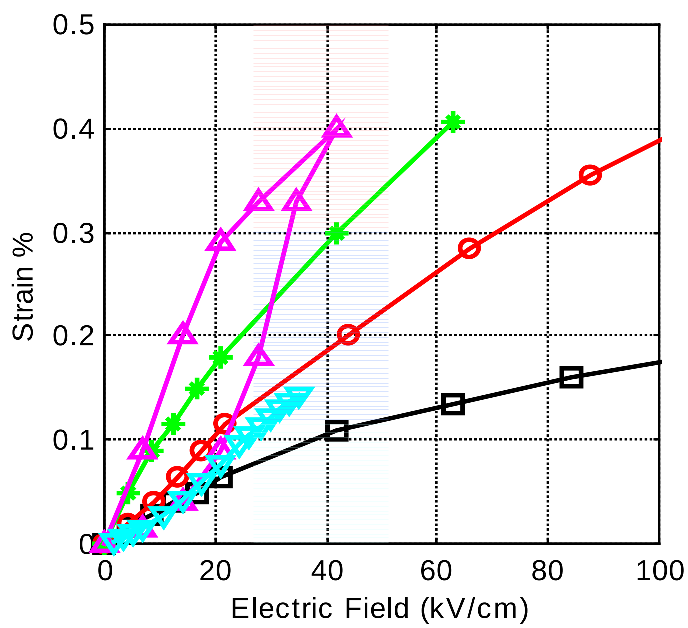
Trial Application Simulation

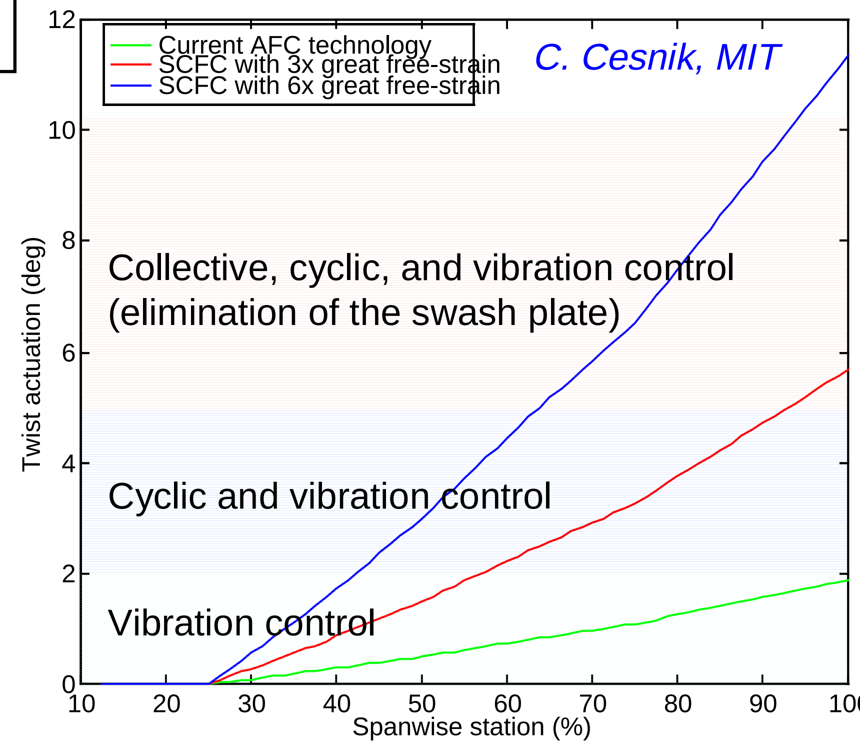
BOEING

Higher authority from Single Crystal Fiber Composites could allow the elimination of complex mechanical systems in rotor craft and benefits in other applications

- PZT-5H
o - PZN-4.5%PT
* - PZN-8%PT
Δ - NBT-2.6%BT
∇- PZT-5A AFC (current)

Standard AFC technology
(0.13% strain at 27 kV/cm p-p)
AFC distributed evenly





- Spanwise twist distribution based on NASA LaRC/MIT blade design & data

Summary

Have brought a unique new technology from the lab into commercial reality

- *Advances in materials technology & processes*
- *Furthered the knowledge in field of active materials*

Have demonstrated properties that meet the needs of demanding military & commercial applications

- *Properties, performance, and robustness*

Demonstration of AFCs in applications is beginning to illustrate the impact of this technology to solve real problems

- *Technology insertion, unique benefits, applicability to next generation material systems*

BOEING ACTIVE MATERIALS & STRUCTURES LABORATORY NAVSEA NEWPORT Undersea Warfare Center Division PIEZO CONTROL by ACX Cambridge, MA USA CONTINUUM